

Available online at www.sciencedirect.com**SciVerse ScienceDirect**

Energy Procedia 18 (2012) 1583 – 1592

Energy
Procedia

Push-pull converter for high efficiency photovoltaic conversion

Pierre Petit, Michel Aillerie, Jean-Paul Sawicki, and Jean-Pierre Charles

*LMOPS, Université de Lorraine and Supelec, 2 rue Edouard Belin, 57070 Metz, and
IUT de Thionville Yutz, Espace Cormontaigne, 57500 Thionville-Yutz, France France*

pierre.petit@univ-metz.fr

Abstract

The energy conversion systems especially dedicated for the conversion of electrical power from solar generators into a grid are analysed. Lot of systems are basically developed on boosters or inverters including electronic switches such as MOS or bipolar transistors. The limits of efficiency are quickly reached when high output voltages and high input currents are needed. After presentation of some usual classical systems, pointing out their advantages and drawbacks, we propose an original system based on a standard push-pull converter associated with a dynamic modulation control. The main advantage of this combination is the possibility to control the delivered electric power in a wide range between very low to high levels within the same basic architecture.

© 2012 Published by Elsevier Ltd. Selection and/or peer review under responsibility of The TerraGreen Society.
Open access under [CC BY-NC-ND license](https://creativecommons.org/licenses/by-nc-nd/4.0/).

Keywords: Photovoltaic, converters, MVDC, MVAC, Solar, Power MOS, Push-Pull, Boost, Inverter

1. Introduction

Photovoltaic (PV) systems optimization drives a lot of research works towards solutions for direct power conversion [1-2]. We can classify converters according to the voltage range in which they operate. In cases of applications for power production in isolated sites, low voltage systems were variously studied and optimized for storage in accumulators [2]. They present the advantage to convert low voltages, which is suitable to the integration of standard semiconductor components as MOS and bipolar transistors having low losses in this operating range [3-6]. This trivial solution as regards to the autonomous systems such as the intelligent recharging accumulators is not suitable for direct power production interconnected to a grid, in which case an increase of the voltage is needed before ac conversion and connection. [7]

In this case, one has to involve dc/dc step-up systems followed by dc/ac converters or directly dc/ac step-up systems driven to adjust the level and frequency of the output voltage synchronized with those of

the grid [8].

The structures of step-up transformers are limited by their architecture as well as by the technology of the power active components that they integrate needed for the power conversion. The main problem met on step-up system transformers is the poor efficiency of the power components working at middle range voltages [7].

These step-up systems among others for various applications including the photovoltaic one were also recently improved and variously treated by authors in literature [9-10]. An important number of step-up structures using active switching components were proposed for photovoltaic systems with converters associated to individual or to a set of parallel, series or mixed associated photovoltaic panels. These systems were particularly intended to be used in a photovoltaic environment and must have a high efficiency. Indeed, the values of acceptable lower limits for the efficiency of such a system announced by AC converters manufacturers are located in a range from 96 % to 99 % [11, 12].

To achieve such a performance level, recent studies showed the interest of the use of distributed architectures to achieve high efficiency in the production [7, 12, 13].

Thus, within this context, we have studied actual solutions existing for middle range voltage conversion dedicated for renewable as photovoltaic energy production and we point out advantages and drawbacks of these systems. Following the conclusions of this analysis, we propose an original architecture allowing the achievement of a high efficiency system. The principle adopted is the direct connection of the PV panels to a grid with a working point fixed at a continuous voltage in the 160VDC to 500VDC range chosen as function of the nominal voltage of the charge. The main developed structure proposed for this approach is shown in Fig.1.

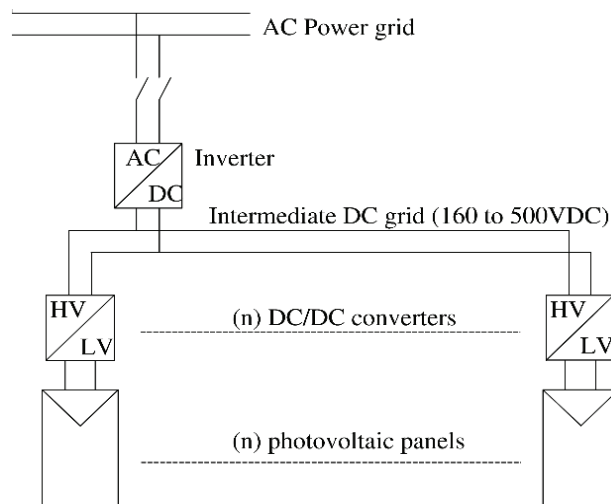


Fig. 1. Schematic of a basic parallel smart grid structure

In our study, the minimum overall level efficiency considered as acceptable in a PV converter system was fixed at 95 %. Thus, by taking into account the fact that the three main active elements of standard converters, which are the inductor, the transistor, and the free wheel diode are the most sought after, the correct distribution of the losses that we have to consider for each component brings a very low maximum level of losses equal to 1.6 %. It is of course obvious to consider the hypothesis that the inductor and the diode are the two elements easiest to size [7].

2. Basic converters

We introduce and comment in this part two basic converter structures, which summarize the converter principles, used as the starting point for the development of the novel push-pull architecture presented in the following of the present publication; this presentation is willingly not exhaustive and reader can get a more complete overview of various converter architectures in the many books and publications related to this subject.

2.1. Buck converters

These systems are widely described and analysed in numerous studies due to the fact that they were the first ones to have been experimented for the optimization of autonomous systems load on accumulators [14-16]. In these pulse-width modulation (PWM) systems, a switching device adjusts the input energy produced by the solar panels to transfer it without stress and with a minimum of power losses to the storage device often working at a fixe voltage level. The schematic diagram of such a system is given in Fig. 2.

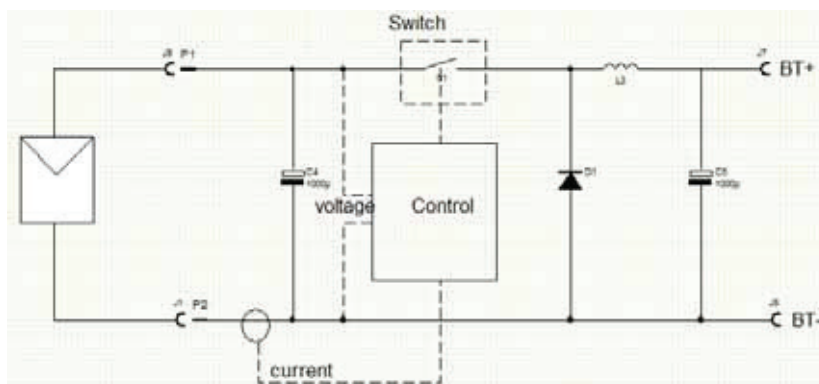


Fig. 2. Basic structure of a Buck converter.

The PWM duty cycle and frequency controlling the energy transfer depends essentially on the value of the input and output voltages. The main advantage of the buck converters consists in the fact that it presents high efficiency for applications in which a decrease of the voltage is necessary while keeping the maximum of the power provided by the solar panel (corresponding to a functioning point located at the maximum power point (MPP) of the P-V characteristic of the PV generator). This simple structure is also well adapted for other non-solar low-voltage applications in renewable energy production systems. Nevertheless, as considered in the specifications of the present study, i.e. for converters presenting an output voltage higher than the input one, namely for step-up voltage converters, the buck converter architecture is technically inadequate due to the high voltage conversion ratio requiring high PWM duty cycle and frequency.

2.2. Boost converters

Boost converters or "elevators" allow to increase the voltage of the source to get an high voltage DC (HVDC) output allowing the direct electrical alimentation of high power charges or interconnection with a HVDC grid [12, 17]. We have represented in Fig. 3, a typical step-up boost converter.

In this structure we can see that the output voltage is applied to the transistor when the diode is on, in the recovery state. As a consequence, the maintain voltage of the transistor must be greater than the expected output voltage. As for converters presented above, the duty cycle and frequency of the PWM command of the switching device (MOS transistor, IGBT etc.) is in a direct relationship with the V_{out}/V_{in} voltage ratio with, in case of energy generation applications as considered in PV production, only V_{out} is fixed at a constant value.

Thus, the specific technological key concerning the functioning of these converter types is the power MOS transistor used as switch. A recent publication [7] shows that, within this switch configuration, it is impossible to obtain output voltages above 150V with a global high efficiency. In fact the $R_{ds(on)}$ resistance of a MOS increases in an over-linear mode according to the maximum voltage rating, and as a direct consequence, induces a huge increase of losses directly link to it.

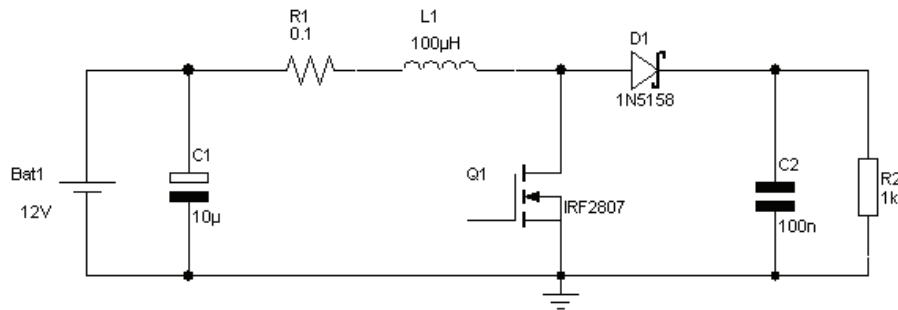


Fig. 3. Basic structure of a Boost converter.

Thus, the specific technological key concerning the functioning of these converter types is the power MOS transistor used as switch. A recent publication [7] shows that, within this switch configuration, it is impossible to obtain output voltages above 150V with a global high efficiency. In fact the $R_{ds(on)}$ resistance of a MOS increases in an over-linear mode according to the maximum voltage rating, and as a direct consequence, induces a huge increase of losses directly link to it.

The main drawback of this type of system is the poor efficiency when the conversion ratio approaches 4. Beyond this voltage ratio, the asymmetry of the signal renders impossible the use for powers exceeding an order of 100 Watts. Beyond this voltage ratio, the asymmetry of the signal renders impossible the use for powers exceeding an order of 50 Watts.

Nevertheless, these step-up systems were considered because of the possibility that they offer to modulate the converted power, thanks to the PWM command on the switching component (the transistor MOS see Fig. 3).

The drawbacks described above of conventional boost systems are mainly linked to the overall generator configuration when energy sensors as panels in photovoltaic applications are connected in string configurations inducing the necessity of high voltage converters. To avoid these drawbacks, distributed architectures using low voltage converters with high efficiency could be an advantageous solution. [18-20].

The schema of Fig. 4 summarizes the distributed structures. Each converter works in an independent way of the others and, fixed at his own MPP of the individual P-V characteristic converts energy in a operating range where transistors can present their highest efficiency. Another advantage of this solution in case of PV applications when each converter is associated with an independent, but synchronize tracker, who follows the maximum power point (MPP) is that each panel can give the maximum available power, even in case of non-uniform sunshine or partial shadow of the PV generator.

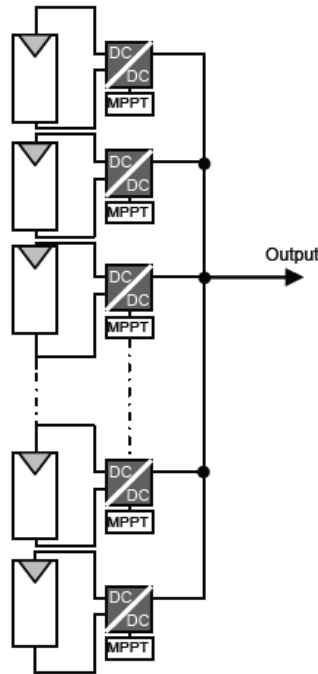


Fig. 4. Distributed PV structure with DC/DC converters

3. The push-pull boost converter

To optimize the global efficiency of the boost converters based on classical inverters described above, we designed a converter with a symmetric architecture using push-pull structure. The problem is in the fact that the output voltage produced by this converter is constant and only dependent with the transformation ratio of the transformer, instead of a current transformer more matched to this kind of use.

The Fig. 5 represents the electronic schema of the proposed boost voltage converter using the push-pull structure. We can clearly observed in this schema the symmetrical structure of the output stage. Within this configuration, the transformer works in a forward mode at high frequencies (>15 kHz), and, thus, it allows the possibilities to minimized the coupled coils element even in case of conversion of high powers. Moreover, the symmetrical structure of the push-pull stage allows the use of the two quadrants of the magnetic cycle of the transformer, the main advantage being the size optimization of the coils. With well-dedicated magnetic circuit, one can obtain a negligible air gap inducing a high AI inductance avoiding possible saturation of the magnetic element.

Within this configuration, the voltage transfer ratio of the converter is given by those of the transformer itself, i.e. $m = V_{out}/V_{in} = N_2/N_1$, with N_2 and N_1 , the number of turns of the output and input coils of the transformer, respectively. Considering these equations, the impedance ratio can be written as $m^2 = Z_{out}/Z_{in}$, which shows the possibility to adapt the impedance transfer between the PV panel and the grid.

In our study, we can see in the electronic schema of the converter analysed and represented in Fig. 5, that we have chosen two carbure - silicium rapid rectifier diodes. The converter also integrates new generation rapid components allowing an optimal power transfer. The efficiency of such solution can be advantageous when high voltage holding is requested (in our simulations, we have considered

$V_{out} = 600V$) compared with those of systems integrating Schottky diodes. An additional inductor connected in series with the output coil gives a global behaviour similar to a classical Step-Up. It allows a positive voltage gap between the output voltage load (HVDC bus) and the necessary upper voltage at the output of the push-pull converter providing from the PV sources after amplification by the transformer.

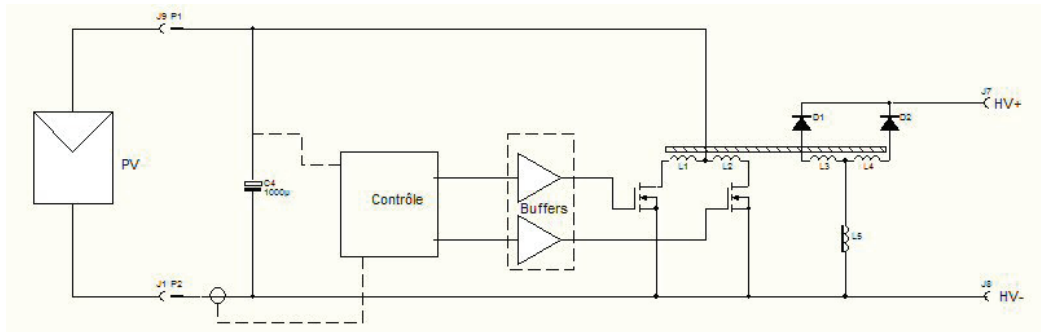


Fig. 5. Schematic structure of a push-pull converter

This converter also integrates a PWM system to adjust the MPP of the power extracted from the panel. It has a global behaviour like a voltage generator related to the panel voltage in serial with a switch commended by the PWM control as seen in Fig.6 in which the voltage generator is named G.

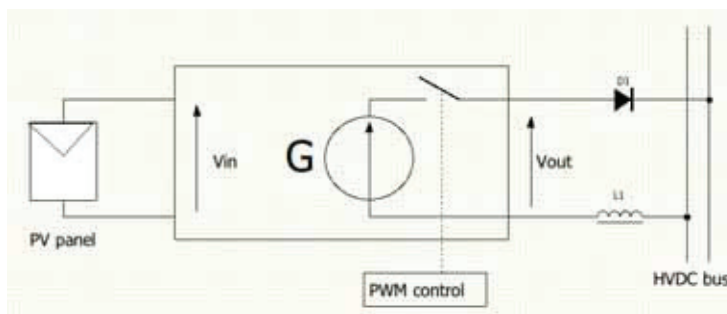


Fig. 6. Equivalent generator of a PV panel connected to a HVDC bus.

The MOS driving in G, which can be assumed by a microcontroller, is synchronized and generates pulses for the two part of the push-pull switches in opposite phase.

It is to be of note that due to the fact that a positive voltage gap exists between the HVDC bus and the output voltage of the converter obliges to extract the energy in a discontinue way. Thus, this operating mode imposes a burst mode for the pulses applied to the two switches.

3.1. Push-pull boost converter behaviour simulation

We have evaluated the performance of the push-pull boost converter with a PSPICE model, represented in Fig. 7 and using the simulation tools based on ORCAD to establish voltage and current values and shapes.

We note in this schema in Fig. 7 the two drivers for the switches in the primary stage and an inductor

in the output stage, in series with the two coupled inductors adding to avoid high transient variations of the current in the transformer, and, as a consequence by forward effect in the PV panel.

The resulting chronograms of simulations show very precisely the evolution of one of the output coil named V(R6:1). We can see some pseudo periodic oscillations du to the resonance between the inductors and parasitic capacitors present in the circuit. We have also reported the voltage shapes of the drain (V(M3:d)) and gate (V(U1:output)) voltages of one MOSFET. We observe some over voltage on the drain MOSFET that indicates the necessary improvement of the transformer-coupling factor. In this figure, we clearly show the burst mode on the PWM signal MOSFET control.

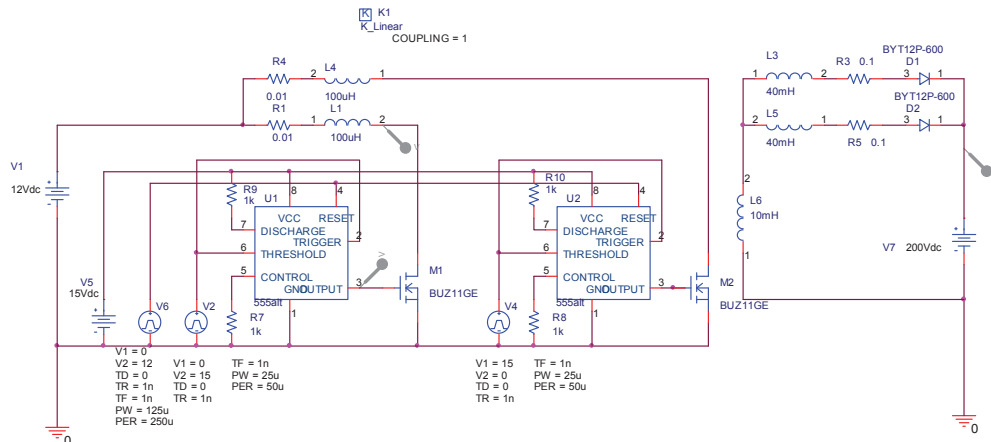


Fig. 7. Schematic used for the simulation of the push-pull converter by ORCAD simulator.

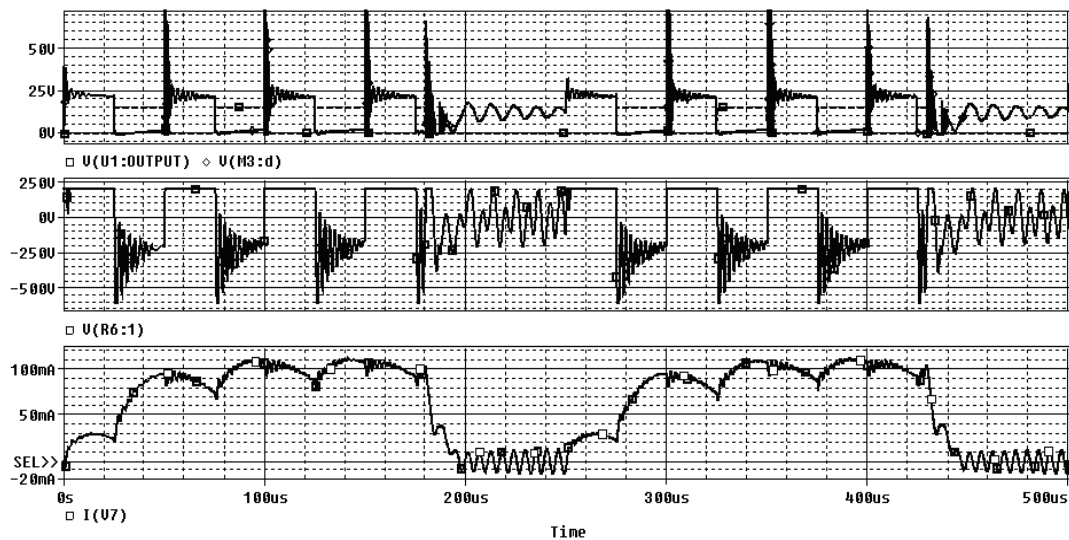


Fig. 8. Top: MOSFET command (in dash), and drain voltage of one MOSFET. Bottom: Output secondary current injected into the HVDC bus symbolized by V₁ in the diagram of Fig. 7.

For the simulation, the choice of a DC voltage generator as an equivalent of the HVDC bus has been preferred to a simple resistive load. Then, we can observe the power transfer by analysing the DC current provided into the bus. Nevertheless, in practice when the system is connected to the HVDC bus, no change in the operating mode occurs in comparison with this simulating mode done with a resistive load.

With the use of such a system, one can expect many advantages in terms of signal quality due to the high symmetry of the currents in continuous mode, in terms of cost by the use of low voltage MOS transistors and in terms of efficiency.

3.2. Implementation of a push-pull boost converter

The implementation of such a system implicates some additional control organs designated to the supplies stabilization on one hand, and the acquisition vector measurements at the other hand. The complete implementation schematic is reported in Fig 9 and the prototype is shown in the picture of Fig. 10.

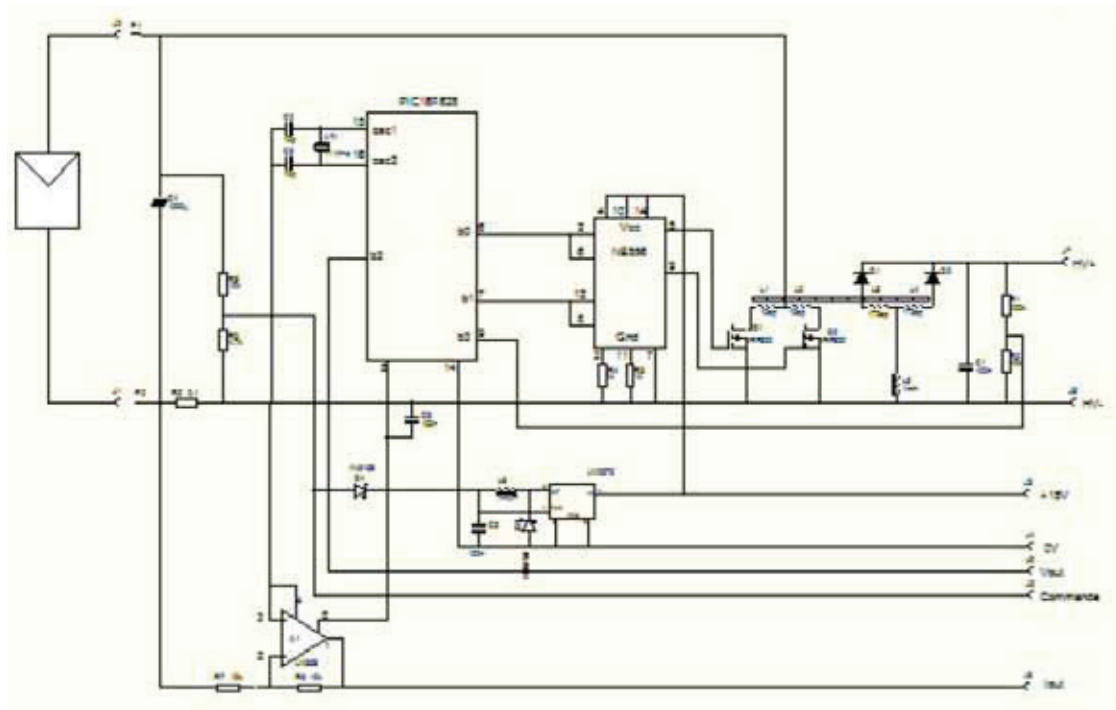


Fig. 9. Schematic used for the simulation of the push-pull converter by ORCAD simulator.

The tracking of the MPP and the driving of the PWM signal is made by a 8 bits micro-controller in charge of the functioning stability in static and transient modes, which drives the two MOSFETs buffer inputs. The choice of a micro-controller for the driving of the converter brings flexibility and allows the integration of such a converter in the multi-generators parallel architecture connected to an inverter and also, enables the possibility of communication with a monitoring system.



Fig. 10. Prototype of the push-pull converter.

4. Conclusion

This paper has proposed a novel converter based on a push-pull architecture associated with a magnetically couple transformer. This specific architecture provides high efficiency and high step-up DC-DC conversion with the possibility of an independent impedance adaptation single link to the converter ratio of the transformer. Additionally, we have shown that the addition of an inductance in the output stage avoids fast transient currents in all parts of the converter. The steady state analysis of voltage gain and boundary operating condition are partially discussed. Due to its symmetrical operation with two switch elements, this structure allows the possibility to obtain a high conversion ratio. Finally, the presentation of the implementation of such a converter with the realization of a prototype shows the possibility of its integration in distributed photovoltaic generator architectures.

Acknowledgements

Authors are grateful to Abdallah Zégaoui, PhD, for the fruitful discussions on various converter architectures applied to renewable energy system.

References

- [1] Oozeki T. Advanced analysis of shading effect using minutely based measured data for PV systems, Tokyo University of Agriculture, Shanghai China 2005.
- [2] Villalva J. M. G., Filho E.R. Comprehensive approach to modeling and simulation of photovoltaic arrays. *IEEE Trans. Power Electron.* 2009; **24**, 4: 1198–1208.
- [3] Trievdi M. Performance modeling of power MOSFETs. *IEEE Trans. Electron.Devices*, 1999; **ED-46**:1794 -1802.
- [4] Goebel H., A unified method for modeling semiconductor power devices. *IEEE Trans. Power Electron.* 1994, **9**:497-505.
- [5] Lou K. H., Liu C. M., Kuo J. B., Analysis of the quasi-saturation behavior considering the drain-to-source voltage and cell-spacing effects for a vertical DMOS power transistor. *Sol. State Electron.* 1993; **36**, **1**:85 -91.

- [6] Darwish M. Study of the quasi-saturation effect in VDMOS transistors. *IEEE Trans. Electron. Devices* 1986; **ED-33**, 11:1710 - 1716.
- [7] Petit P., Zegaoui A., Sawicki J.P., Aillerie M., Charles J.P. Rdson behavior in various MOSFET families. *IEEE Industr. Electron. ISIE 2011* DOI: 10.1109/ISIE.2011.5984184, 2011; 353-357.
- [8] Zegaoui A., Aillerie M., Petit P., Sawicki J.P., Charles J.P., Belarbi A.W. Dynamic behaviour of PV generator trackers under irradiation and temperature changes. *Solar Energy* 2011; **85**:2953-2964.
- [9] Vighetti S. Systèmes photovoltaïques raccordés au réseau: Choix et dimensionnement des étages de conversion, Ph.D. thesis, École Doctorale "Électrotechnique Électronique Automatique et Traitement du Signal; 2010.
- [10] Qun-Zhao L. High-efficiency, high step-up dc-dc converters. *IEEE Trans. Power Electron.* 2003; **18**:1-9.
- [11] Xiong Y. Modeling and analysis of power MOSFETs for high frequency dc-dc converters Ph.D. thesis, College of Engineering and Computer Science University of Central Florida Orlando, Florida; 2008.
- [12] Kim M. G. Boost converter using an energy reproducing snubber circuit. US Patent 5,633,579, 1997.
- [13] Calais M., Myrzik J. M. A., Agelidis V. G. Inverters for single-phase grid connected photovoltaic systems overview and prospects. *Proc. 17th PV Solar Energy Conf. and Exhibition, Munich, Germany*; 2001.
- [14] Redl R., Erisman B. P., Zansky Z. Optimizing the load transient response of the buck converter. *IEEE APEC Appl. Power Electron.* 1998; **1**, c:170-176.
- [15] Li, Q., Wolfs P. J. A review of the single phase photovoltaic module integrated converter topologies with three different DC link configurations. *IEEE Trans. Power Electron.* 2008; **23**, 3: 1320-1333.
- [16] Chomsuwan, K., Prisuwan, P., Monyakul, V. Photovoltaic grid-connected inverter using two-switch buck-boost converter. *IEEE Photovoltaic Specialists Conf.* 2002; 1527-1530.
- [17] Yi-Ping H., Jiann-Fuh C., Tsorng-Juu L. Novel High Step-Up DC-DC Converter With Coupled-Inductor and Switched-Capacitor Techniques, *IEEE Trans. on Industr. Electron.* 2012; **59**, 2: 998-1007.
- [18] Carrasco J. M., Franquelo L. G., Bialasiewicz J. T., Galvan E., Guisado R. C. P., Prats M. A. M., Leon J. I., Moreno-Alfonso N. Power electronic systems for the grid integration of renewable energy sources: A survey. *IEEE Trans. Power Electron.* 2006; **53**, 4: 1002-1016.
- [19] Liang Z., Guo R., Li J. A High-Efficiency PV Module-Integrated DC/DC Converter for PV Energy Harvest in FREEDM Systems. *IEEE Trans. Power Electron.* 2011; **26**, 3: 897-909.
- [20] Walker G.R., Sernia P. C. Cascaded DC-DC Converter Connection of Photovoltaic Modules Geoffrey. *IEEE Trans. Power Electron.* 2004 19, 4: 1130 - 1139.